WHY HAS EARTH NOT WARMED AS MUCH AS EXPECTED?

AND WHY IS THIS SO IMPORTANT?

Stephen E. Schwartz

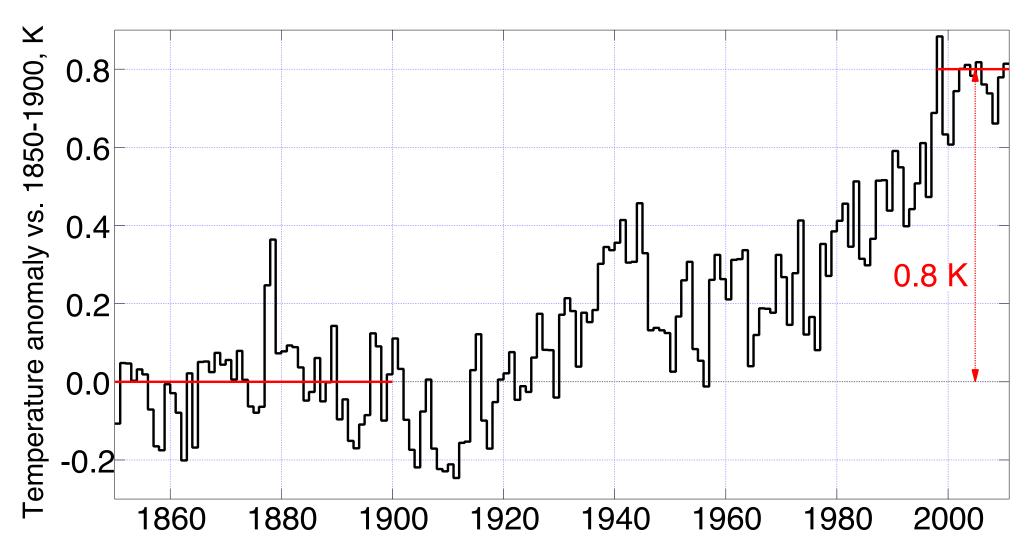
Brookhaven Lecture Series



487th Brookhaven Lecture

May 15, 2013

GLOBAL TEMPERATURE CHANGE SINCE 1850



Climatic Research Unit, East Anglia, UK

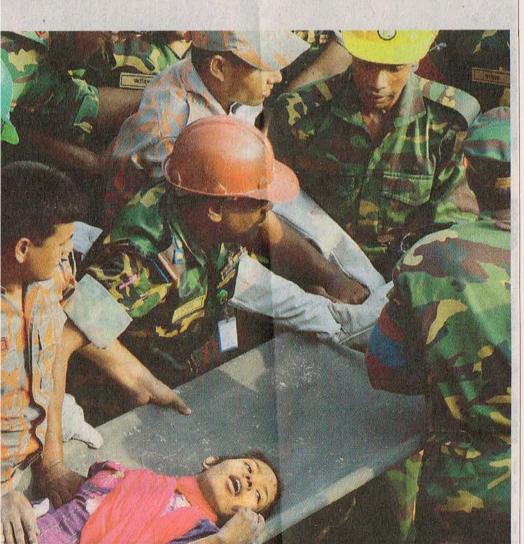
New York Eimes

Late Edition

Today, cloudy, showers, thunderstorms, high 74. **Tonight,** showers, storms, then clearing, low 55. **Tomorrow,** clouds and sun, breezy, high 69. Weather map. Page C8.

NEW YORK, SATURDAY, MAY 11, 2013

\$2.50



Heat-Trapping Gas Passes Milestone, Raising Fears

CO₂ at Level Not Seen in Millions of Years, Portending Major Climate Changes

By JUSTIN GILLIS

The level of the most important heat-trapping gas in the atmosphere, carbon dioxide, has passed a long-feared milestone, scientists reported Friday, reaching a concentration not seen on the earth for millions of years.

Scientific instruments showed that the gas had reached an average daily level above 400 parts per million — just an odometer moment in one sense, but also a sobering reminder that decades of efforts to bring human-produced emissions under control are faltering.

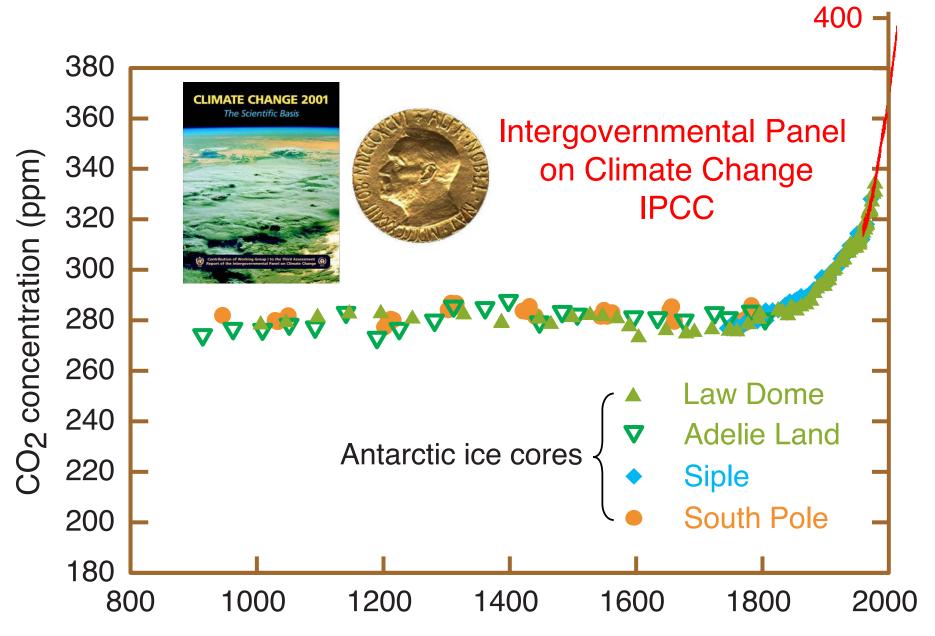
The heet available evidence

the high level.

The new measurement came from analyzers atop Mauna Loa, the volcano on the big island of Hawaii that has long been ground zero for monitoring the worldwide trend on carbon dioxide, or CO₂. Devices there sample clean, crisp air that has blown thousands of miles across the Pacific Ocean, producing a record of rising carbon dioxide levels that has been closely tracked for half a century.

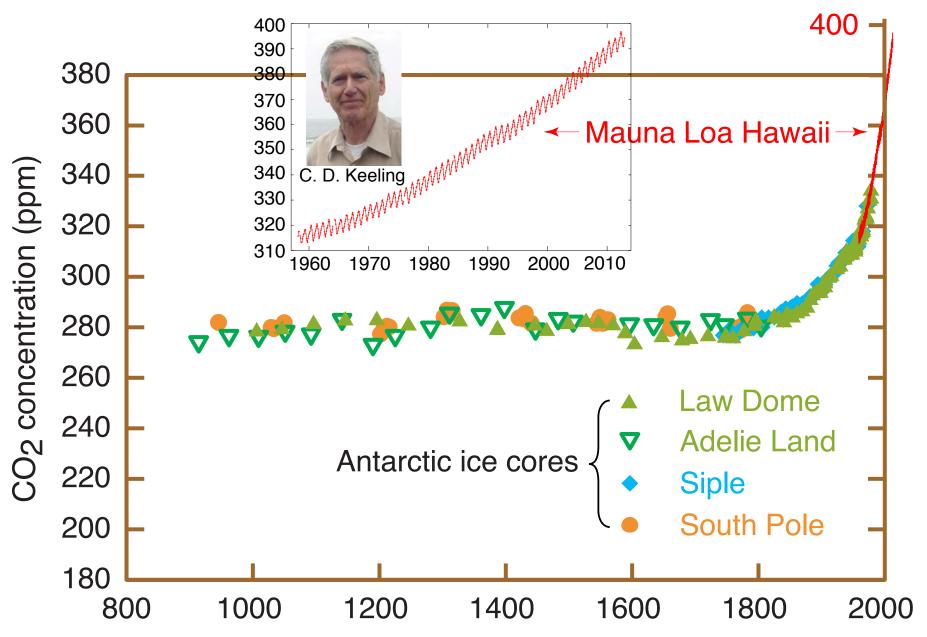
Carbon dioxide above 400 parts per million was first seen in the Arctic last year, and had also

ATMOSPHERIC CARBON DIOXIDE IS INCREASING



Global carbon dioxide concentration over the last thousand years

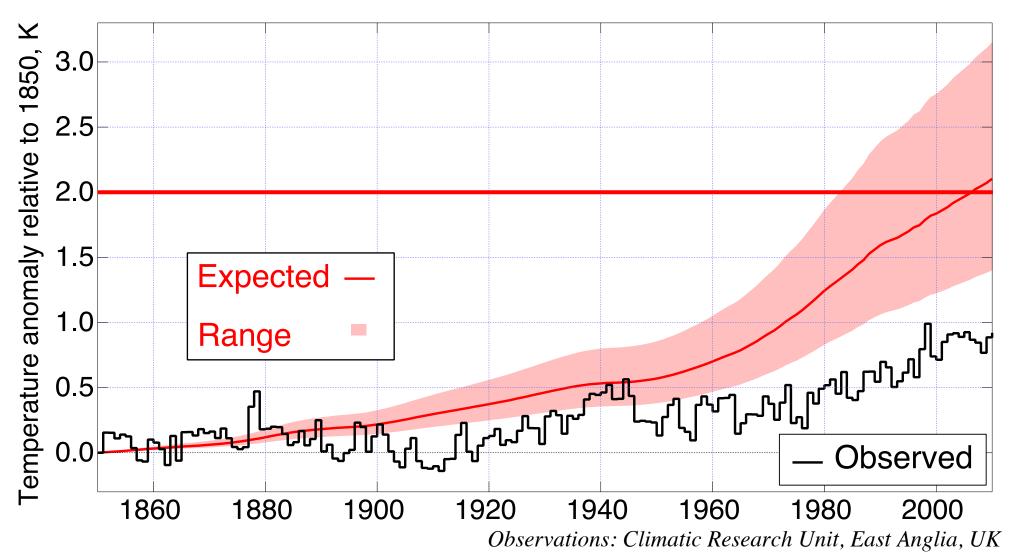
ATMOSPHERIC CARBON DIOXIDE IS INCREASING



Global carbon dioxide concentration over the last thousand years

EXPECTED AND OBSERVED TEMPERATURE CHANGE OVER THE TWENTIETH CENTURY

Expected warming for forcing by long-lived greenhouse gases only



Expected increase equals or exceeds 2 degree threshold.

2009 COPENHAGEN ACCORD AGREES ON 2°C MAXIMUM TEMPERATURE RISE

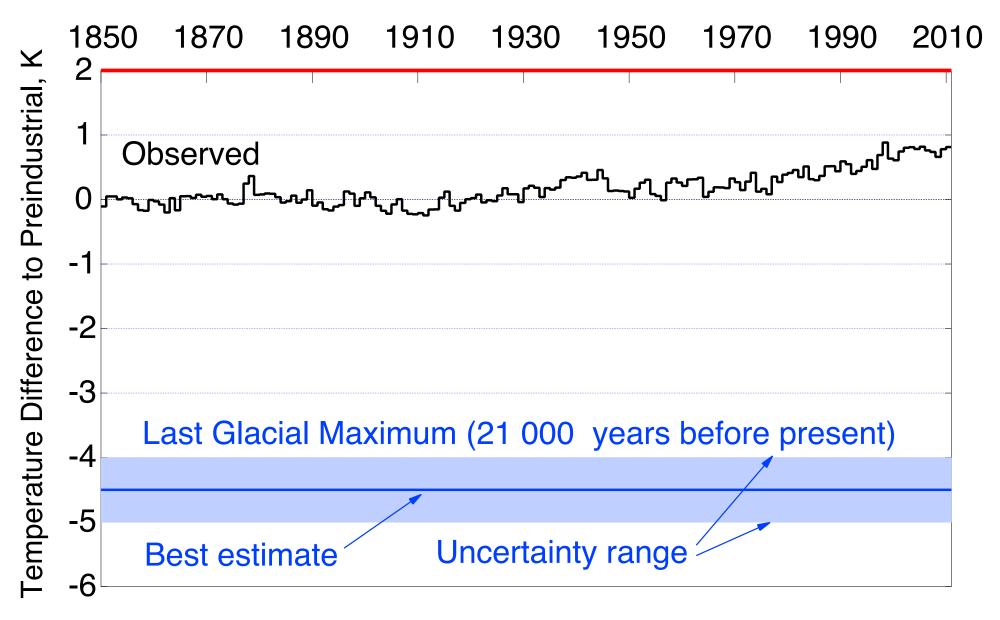
The Heads of State, Heads of Government, Ministers . . . present at the United Nations Climate Change Conference 2009 in Copenhagen:

Albania, Algeria, Armenia, Australia, Austria, . . . [106 countries] . . . , *United States of America*, Uruguay and Zambia, *have agreed* on this Copenhagen Accord. . . .

We underline that climate change is one of the greatest challenges of our time. We emphasise our strong political will to urgently combat climate change. . . .

To ... stabilize greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system, we shall, recognizing the scientific view that the increase in global temperature should be below 2 degrees Celsius . . . enhance our long-term cooperative action to combat climate change.

4½ DEGREES OF SEPARATION



2 Degrees is half of an ice age – BUT, in the other direction!

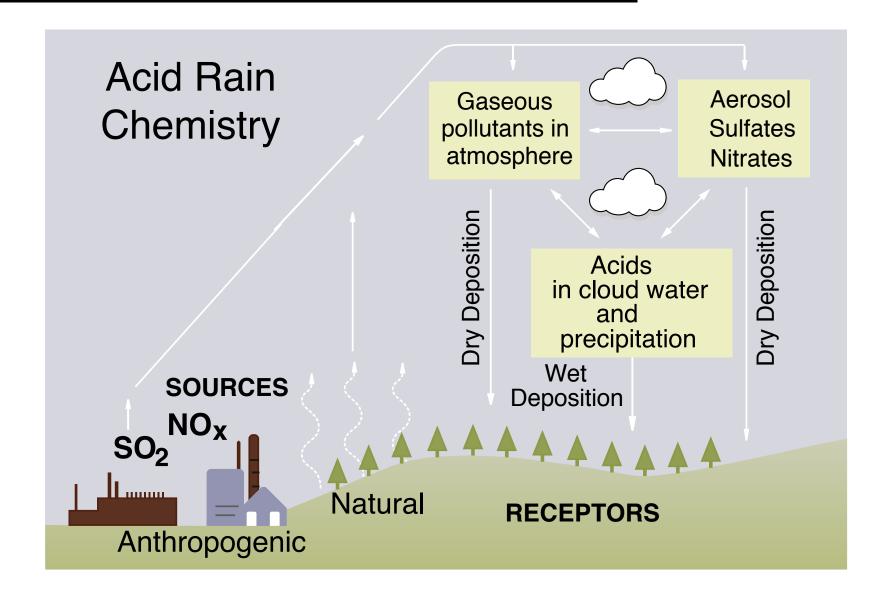
KEY QUESTION

• How much more CO₂ can be emitted without committing Earth to a temperature increase of 2 °C above preindustrial?

Brookhaven Lecture Series



196th Brookhaven Lecture
January 26, 1983
Both Sides Now –
The Chemistry of Clouds



Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate

Robert J. Charlson*, James E. Lovelock*, Meinrat O. Andreae* & Stephen G. Warren*

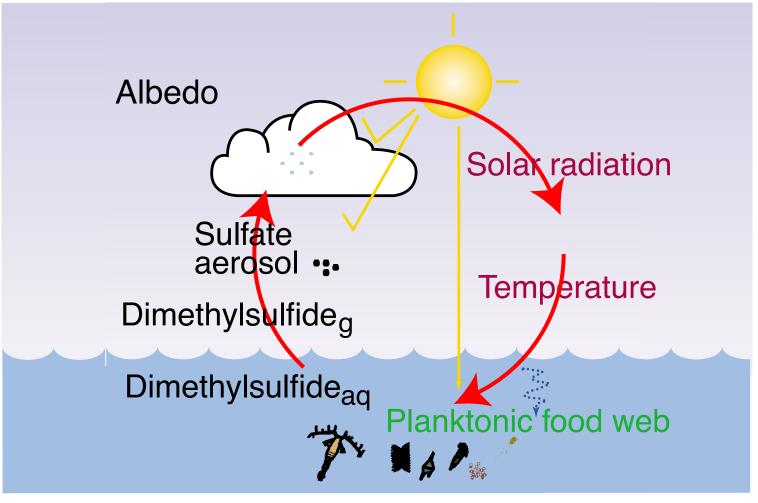


Figure modified from Simo, Trends in E & E, 2001



Are global cloud albedo and climate controlled by marine phytoplankton?

Stephen E. Schwartz

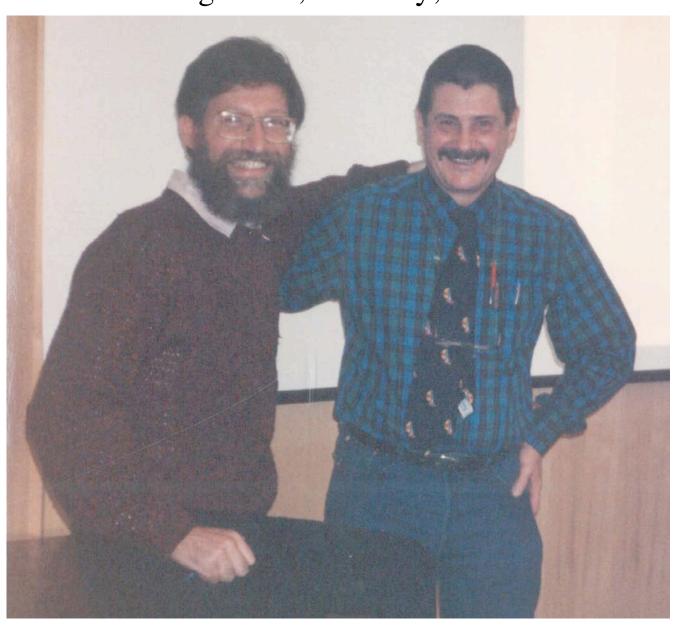
Anthropogenic SO_2 emissions exceed marine emissions of dimethylsulphide globally and are confined largely to the Northern Hemisphere.

Concentrations of *sulphate in aerosol*, *precipitation and ice cores* at remote locations in the NH and SH are *substantially greater throughout the NH* than in remote SH locations.

No influence of SO₂ emissions is found either in the present cloud component of planetary albedo or in 100-year temperature records.

SES with ROBERT CHARLSON

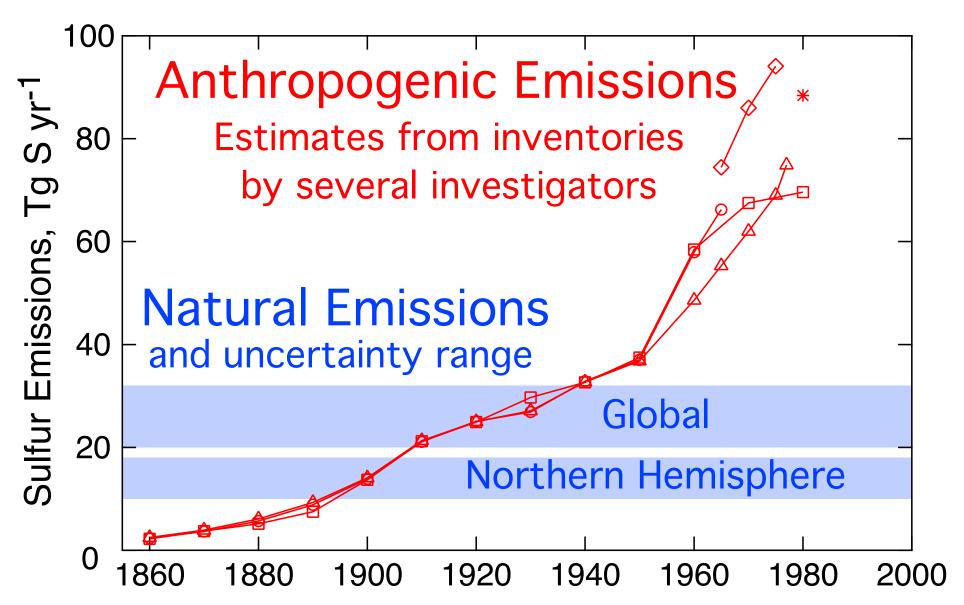
Tegernsee, Germany, 1990



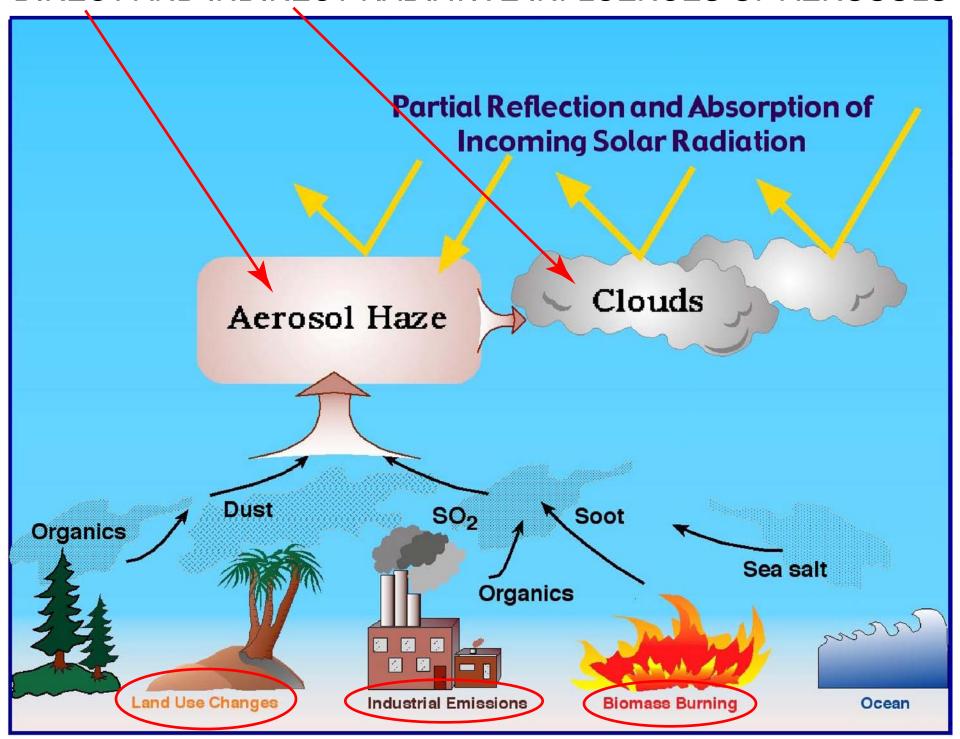
Climate Forcing by Anthropogenic Aerosols

1992 R. J. Charlson, S. E. Schwartz, J. M. Hales, R. D. Cess, J. A. Coakley, Jr., J. E. Hansen, D. J. Hofmann





DIRECT AND INDIRECT RADIATIVE INFLUENCES OF AEROSOLS



ANTHROPOGENIC AEROSOL FORCING

Although long considered to be of marginal importance to global climate change, tropospheric aerosol contributes substantially to radiative forcing, and anthropogenic sulfate aerosol in particular has imposed a major perturbation to this forcing.

Both the direct scattering of short-wavelength solar radiation and the modification of the shortwave reflective properties of clouds by sulfate aerosol particles increase planetary albedo, thereby exerting a cooling influence on the planet.

Climate Forcing by Anthropogenic Aerosols

ANTHROPOGENIC AEROSOL FORCING cont'd

This perturbation is comparable in magnitude to current anthropogenic aerosol forcing has likely offset global greenhouse warming to a substantial degree.

Aerosol effects must be taken into account in evaluating anthropogenic influences on past, current, and projected future climate and in formulating policy regarding controls on emission of greenhouse gases and sulfur dioxide.

Climate Forcing by Anthropogenic Aerosols





Title Climate forcing by anthropogenic aerosols

Authors Robert J Charlson, SE Schwartz, JM Hales, RD Cess,

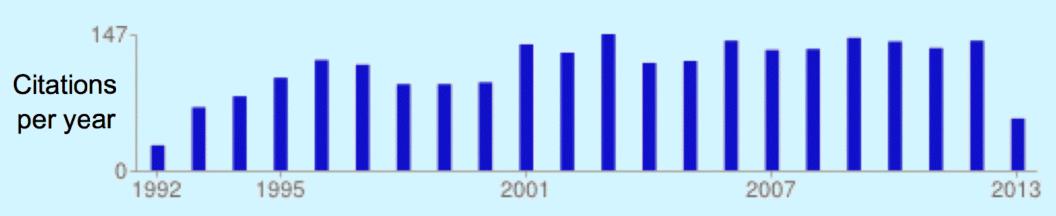
JA Coakley jr, JE Hansen, DJ Hofmann

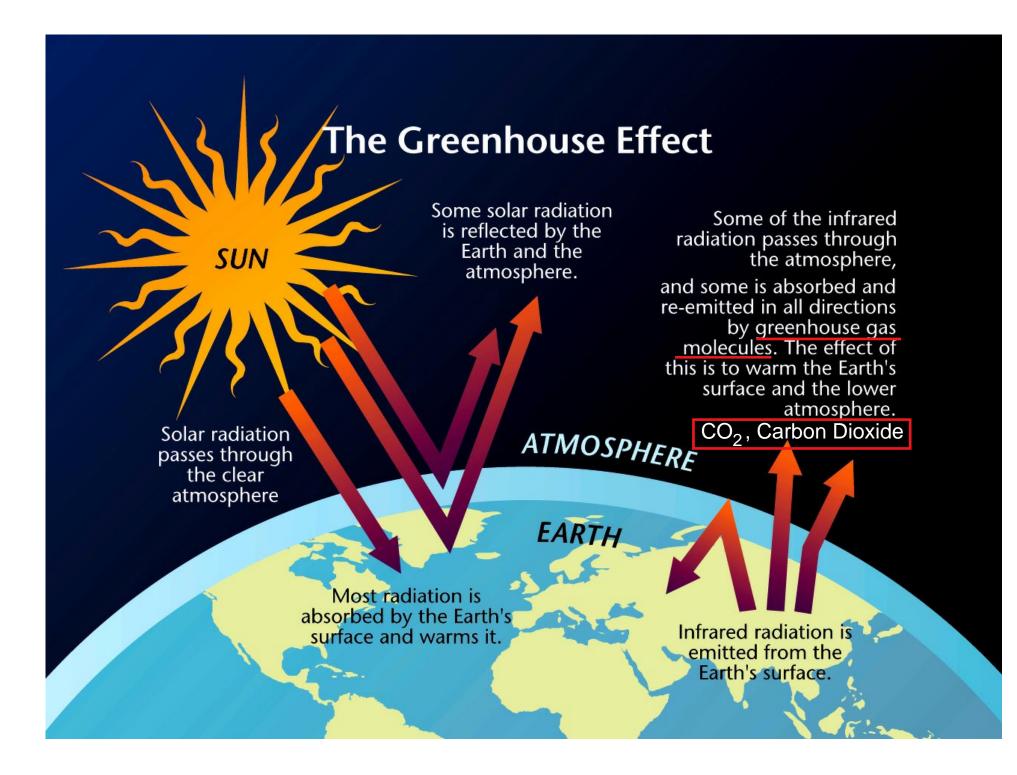
Publication date 1992

Journal name Science

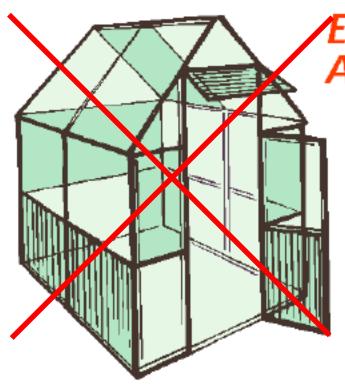
Publisher American Association for the Advancement of







THE GREENHOUSE EFFECT



ÆARTH'S ENERGY BUDGET: A DELICATE BALANCE

- Sunlight heats the Earth.
- The warm Earth radiates energy (in the form of infrared radiation, or heat) back out to space.
- Some of this infrared radiation is trapped in the atmosphere, giving Earth its temperate climate.

This is the greenhouse effect.

Global average temperature 14°C or 57°F Without it, the Earth's climate would be like the moon's, harsh and severe.

Global average temperature -18°C or 0°F

ATMOSPHERIC RADIATION

Power per area

Energy per time per area

Unit:
Watt per square meter
W m⁻²

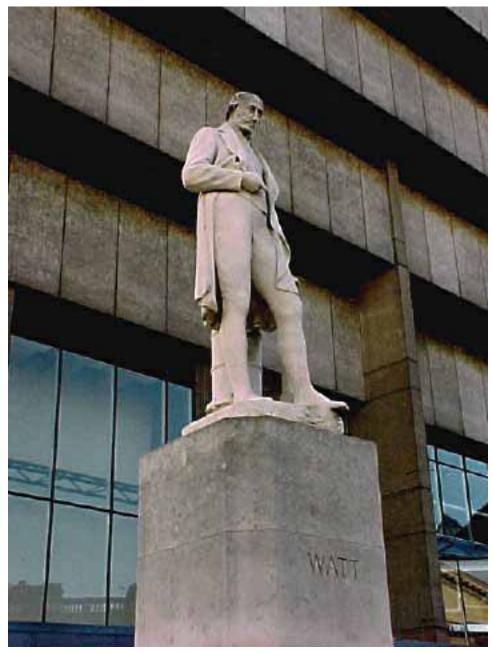
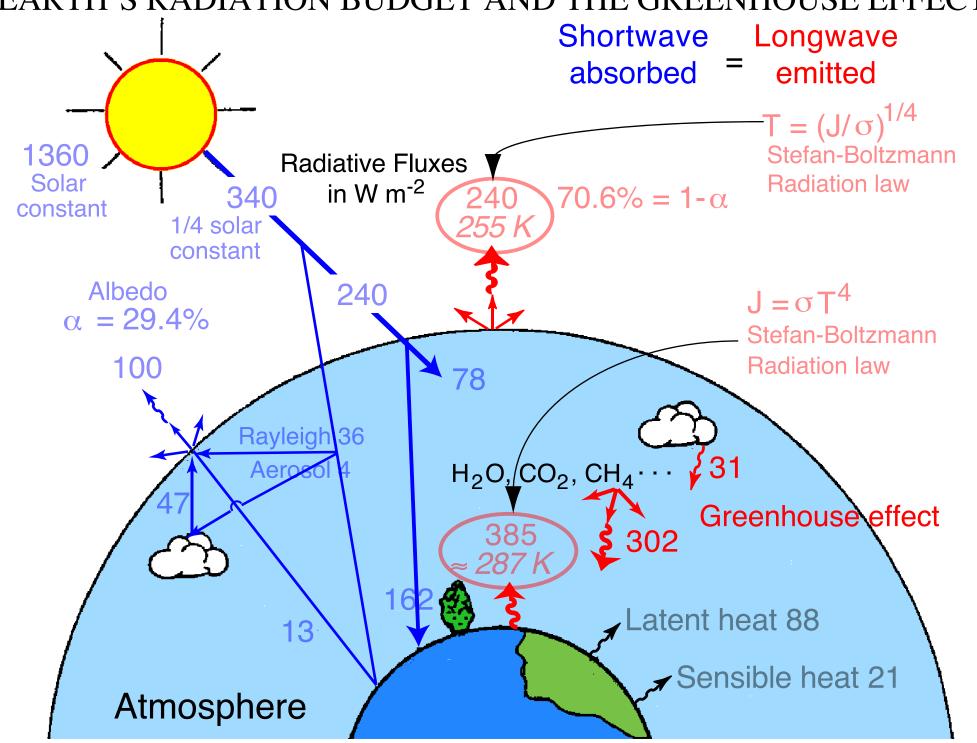


Photo credit: S. E. Schwartz

EARTH'S RADIATION BUDGET AND THE GREENHOUSE EFFECT



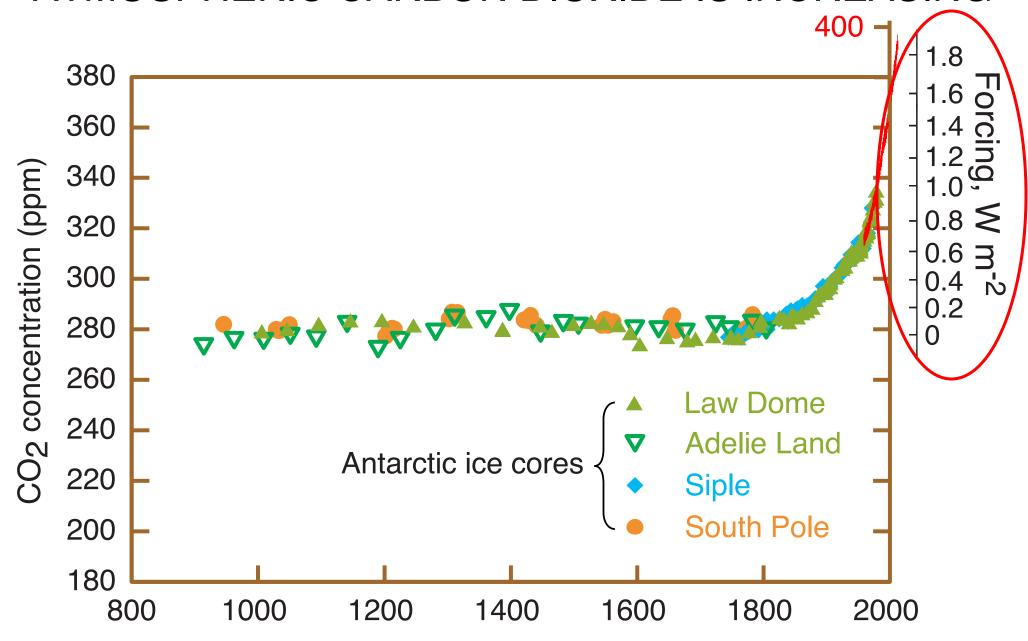
RADIATIVE FORCING

An externally imposed *change* in Earth's radiation budget, W m⁻².

Working hypothesis:

On a global basis radiative forcings are additive and interchangeable.

ATMOSPHERIC CARBON DIOXIDE IS INCREASING

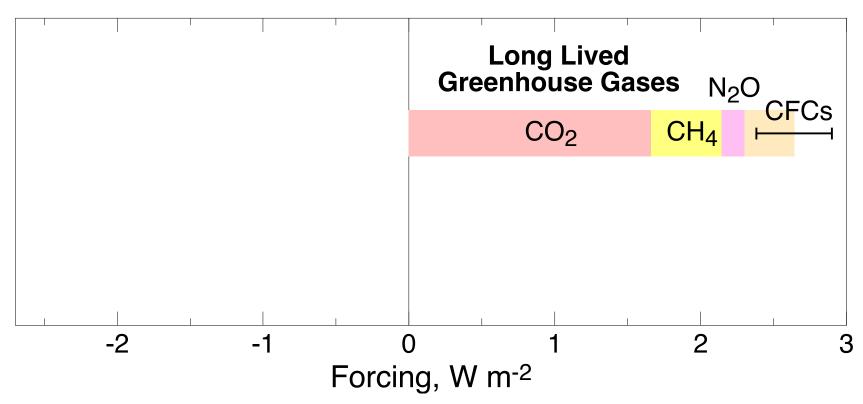


Global carbon dioxide concentration over the last thousand years

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

Extracted from IPCC AR4 (2007)

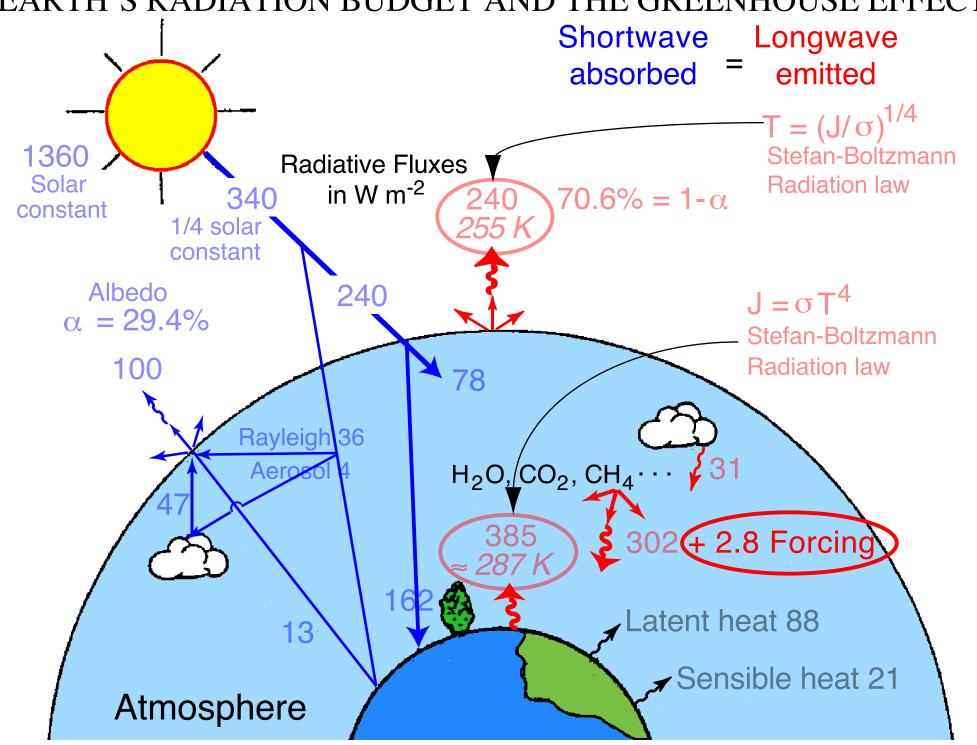




Greenhouse gas forcing is considered accurately known.

Gases are uniformly distributed; radiation transfer is well understood.

EARTH'S RADIATION BUDGET AND THE GREENHOUSE EFFECT



HOW MUCH WARMING IS EXPECTED?

Steady-state change in global mean = Climate sensitivity × Forcing

$$\Delta T = S \times F$$

S is "equilibrium" sensitivity. Units: K/(W m⁻²)

Sensitivity is commonly expressed as "CO₂ doubling temperature"

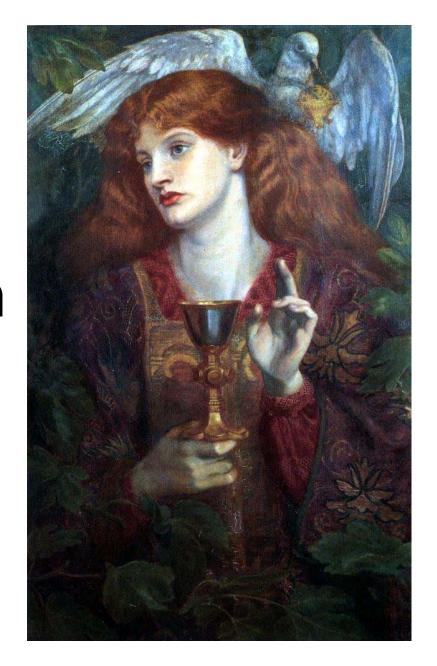
$$\Delta T_{2\times} \equiv S \times F_{2\times}$$

where $F_{2\times}$ is the "CO₂ doubling forcing" $ca. 3.7 \text{ W m}^{-2}$.

Climate Sensitivity

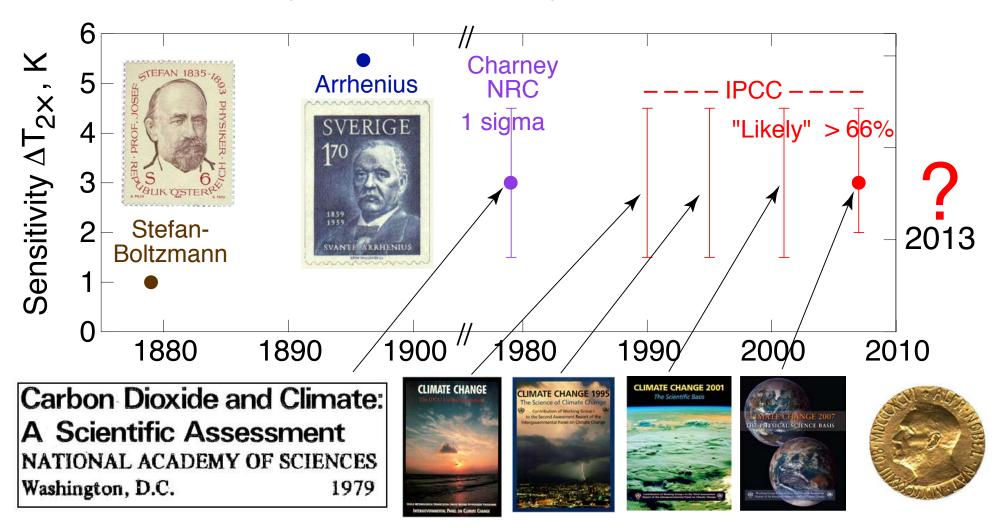
The "Holy Grail" of Climate Research

$$\Delta T = S \times F$$



CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

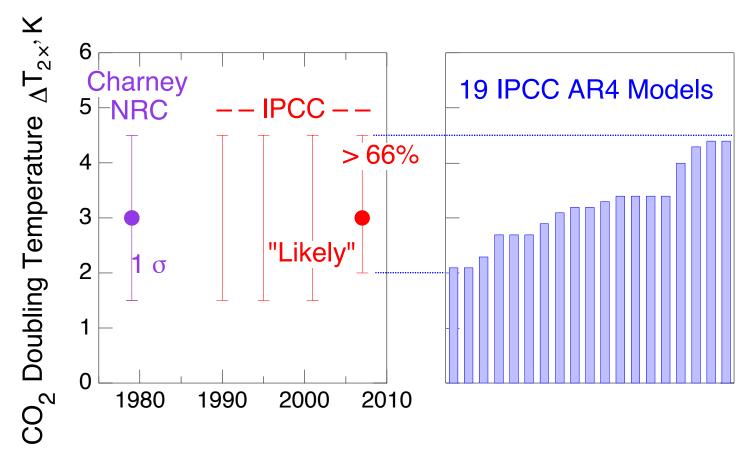
Estimates of central value and uncertainty range from major national and international assessments



Despite extensive research, climate sensitivity remains *highly uncertain*.

ESTIMATES OF EARTH'S CLIMATE SENSITIVITY AND ASSOCIATED UNCERTAINTY

Major national and international assessments and current climate models



Current estimates of Earth's climate sensitivity are centered about a CO₂ doubling temperature $\Delta T_{2\times} = 3$ K, but with substantial uncertainty.

Range of sensitivities of current models roughly coincides with IPCC "likely" range.

?? QUESTION ??

• Why is there such a large range of sensitivities in current climate models and why hasn't this situation improved much in thirty years?

ANSWER

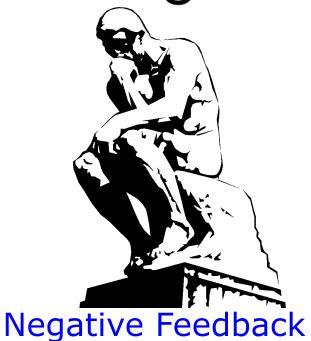
• This is a really tough scientific problem!

Cloud Feedbacks: A Big Mystery in Climate Sensitivity

Higher temperature, Clouds evaporate. More sunlight is absorbed

Positive Feedback Higher Sensitivity

Higher temperature,
More water vapor,
More clouds.
Less sunlight is
absorbed



Lower Sensitivity

HOW MUCH WARMING IS EXPECTED?

For increases in long-lived greenhouse gases (CO₂, CH₄, N₂O, and CFCs) over the industrial period

$$F = 2.8 \text{ W m}^{-2}$$

Expected temperature increase:

$$\Delta T_{\text{exp}} = \frac{F}{F_{2\times}} \times \Delta T_{2\times} = \frac{2.8}{3.7} \times 3 \text{ K} = 2.3 \text{ K}$$

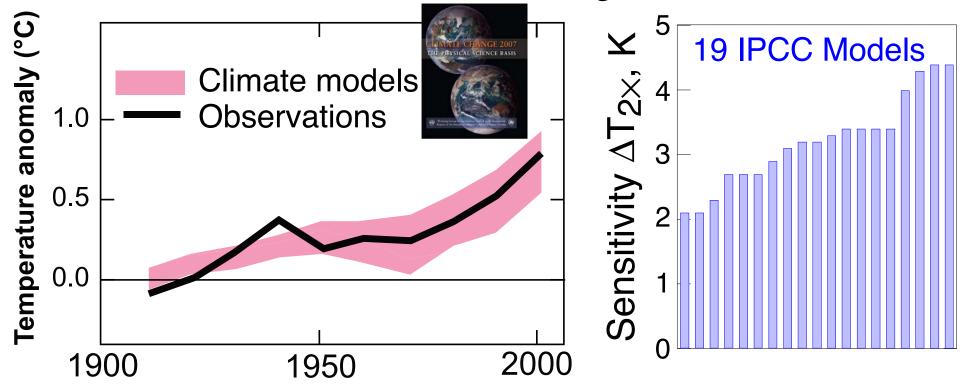
Observed temperature increase:

$$\Delta T_{\rm obs} = 0.8 \text{ K}$$

Warming Discrepancy

OBSERVED AND MODELED WARMING

Ensemble of 58 model runs with 14 global climate models



- 66 Simulations that incorporate anthropogenic forcings, including increasing greenhouse gas concentrations and the effects of aerosols, and that also incorporate natural external forcings provide a *consistent explanation of the observed temperature record*.
- 66 These simulations used models with different climate sensitivities, rates of ocean heat uptake and magnitudes and types of forcings.

IPCC AR4, 2007

From Forcing by Long-lived Greenhouse Gases

Why Hasn't Earth Warmed as Much as Expected?

STEPHEN E. SCHWARTZ

Brookhaven National Laboratory, Upton, New York

ROBERT J. CHARLSON

University of Washington, Seattle, Washington

RALPH A. KAHN

NASA Goddard Space Flight Center, Greenbelt, Maryland

JOHN A. OGREN

NOAA/Earth System Research Laboratory, Boulder, Colorado

HENNING RODHE

Department of Meteorology, Stockholm University, Stockholm, Sweden

WHY HAS EARTH NOT WARMED AS MUCH AS EXPECTED...

FROM FORCING BY LONG-LIVED GREENHOUSE GASES?

- Uncertainty in greenhouse gas forcing.
- Countervailing natural cooling over the industrial period.
- Lag in reaching thermal equilibrium.
- Countervailing cooling forcing by aerosols.
- Climate sensitivity lower than current estimates.

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AEROSOL IN MEXICO CITY BASIN



Photo: Berk Knighton

AEROSOL IN MEXICO CITY BASIN



Light scattering by aerosols decreases absorption of solar radiation.

AEROSOLS AS SEEN FROM SPACE

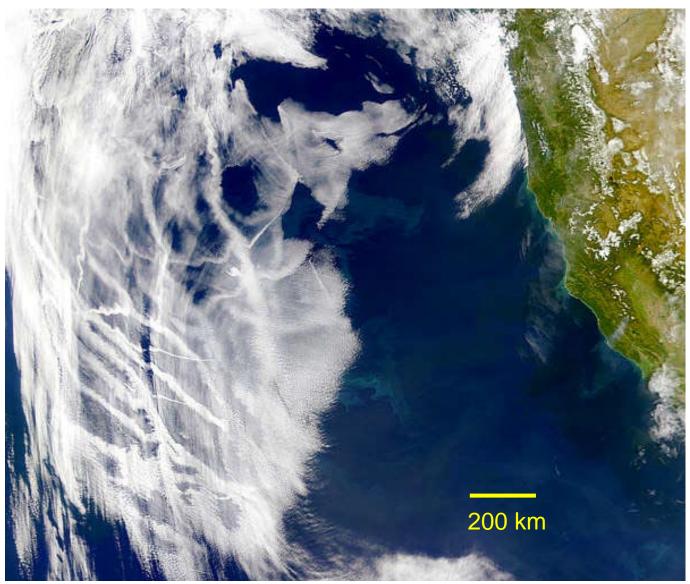


Credit: SeaWIFS

Fire plumes from southern Mexico transported north into Gulf of Mexico.

CLOUD BRIGHTENING BY SHIP TRACKS

Satellite photo off California coast



Credit: SeaWIFS

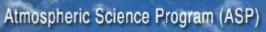
Aerosols from ship emissions enhance reflectivity of marine stratus.

FIELD PROJECTS TO STUDY AEROSOL PROPERTIES AND EVOLUTION



AIRCRAFT MEASUREMENTS







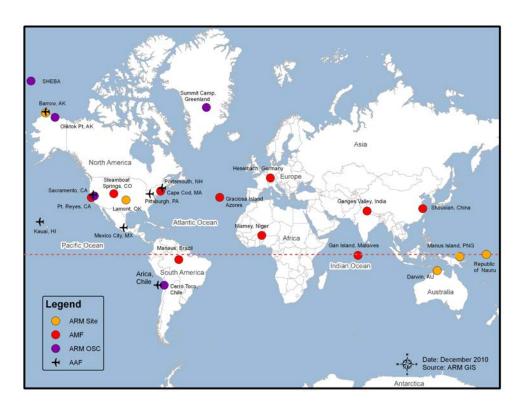






The Atmospheric Radiation Gerald M. Stokes* and Stephen E. Schwartz+ Measurement (ARM) Program: Programmatic Background and Design of the Cloud and Radiation Test Bed





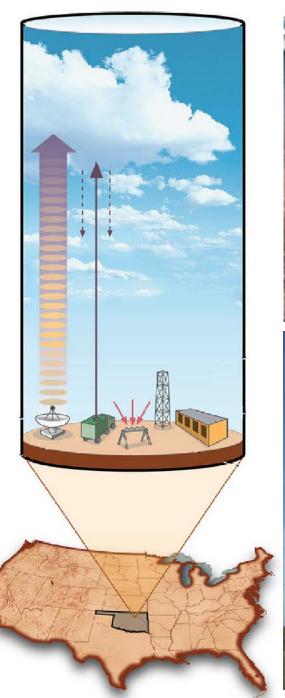




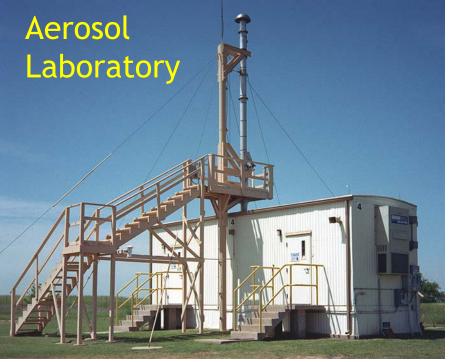




DOE Atmospheric Radiation Measurement Climate Research Facility





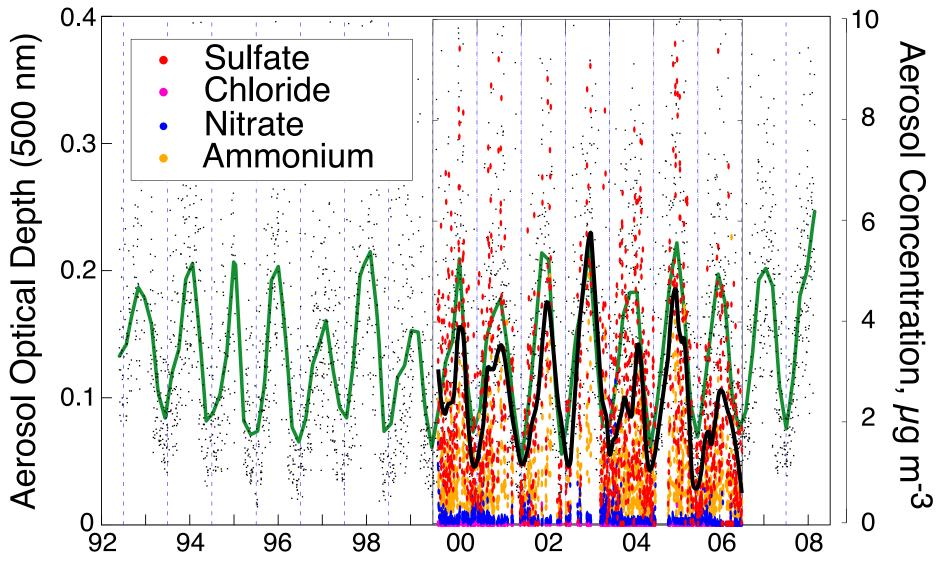






AEROSOL OPTICAL DEPTH AT ARM SGP

Fifteen years of daily average AOD in North Central Oklahoma

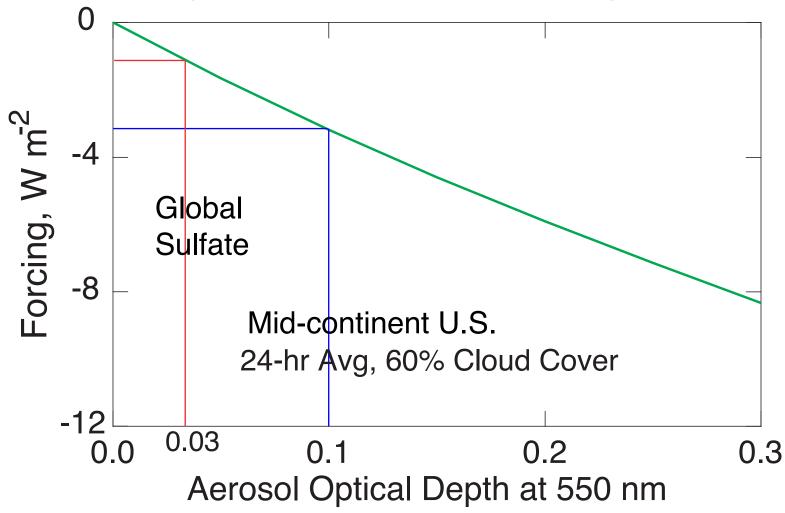


Michalsky, Denn, Flynn, Hodges, Kiedron, Koontz, Schlemmer, Schwartz, JGR, 2010 Chemical data: P. Quinn, NOAA

Green curve, locally weighted smooth fit, shows summertime maximum. Black curve, locally weighted smooth fit to sulfate concentration.

ESTIMATES OF AEROSOL DIRECT FORCING

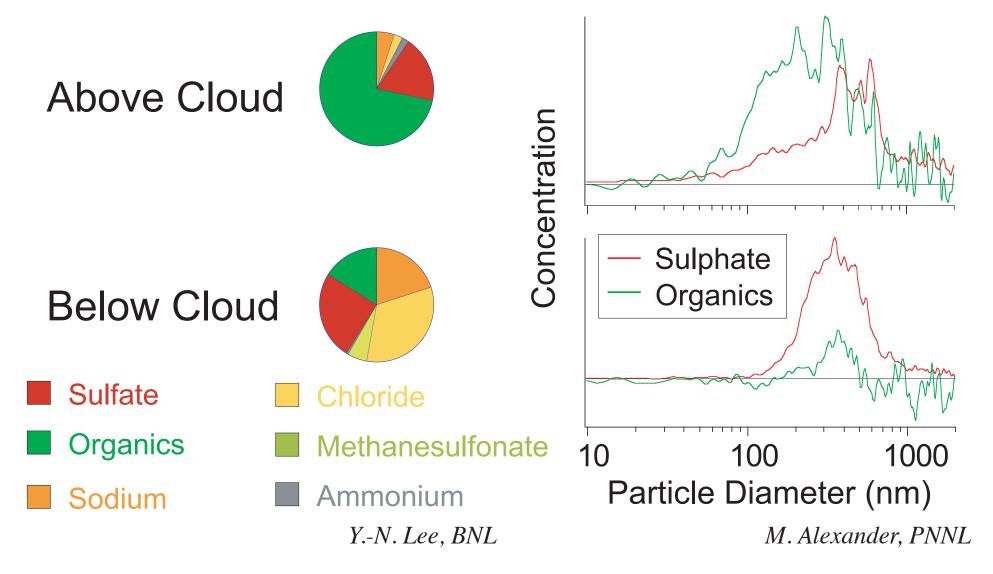
By radiation transfer modeling



Global average sulfate optical depth is 0.03: 1 W m⁻² cooling forcing.

Continental U.S. typical aerosol optical depth is 0.1:3 W m⁻² cooling forcing.

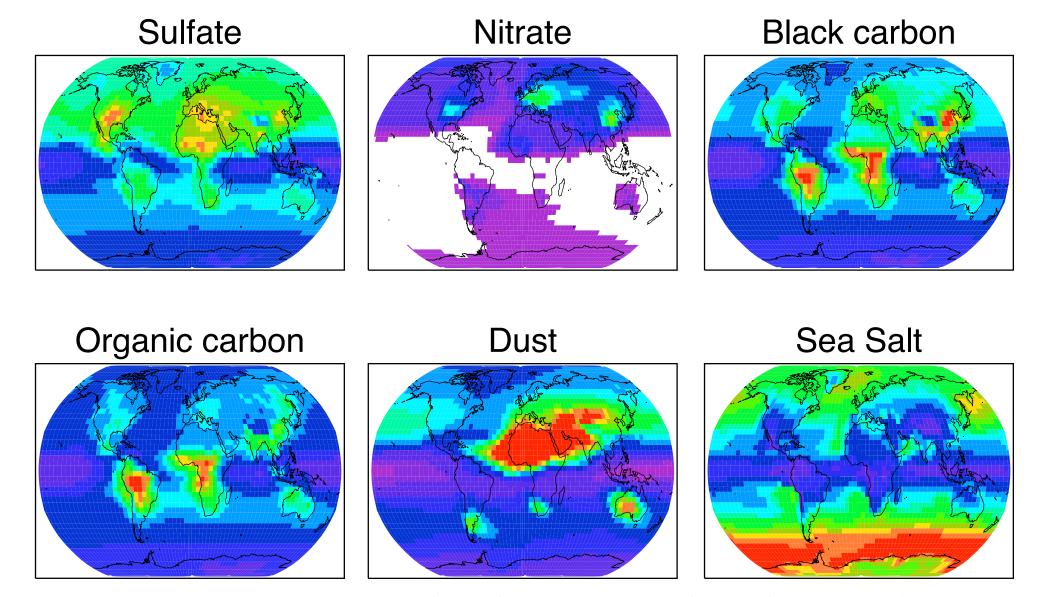
MEASUREMENTS OF AEROSOL COMPOSITION



Aerosol composition depends differently on particle size depending on location relative to clouds, affecting cloud drop formation.

GLOBAL AEROSOL DISTRIBUTIONS

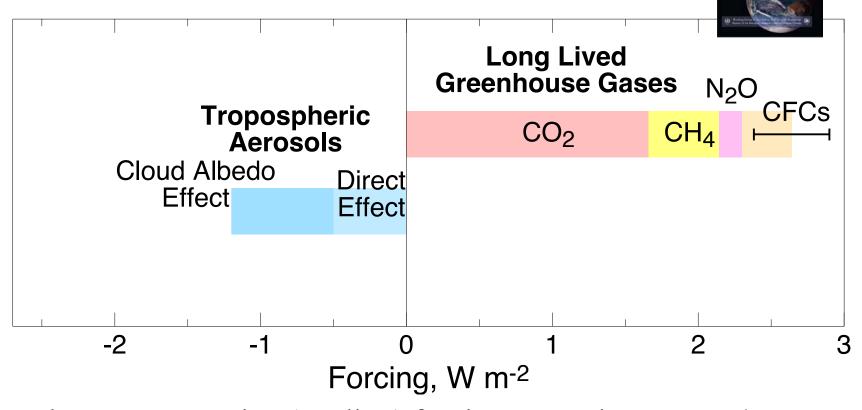
Column amounts of aerosol species calculated with global aerosol model



Bauer, Wright, Koch, Lewis, McGraw, Chang, Schwartz & Ruedy, ACP, 2008

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

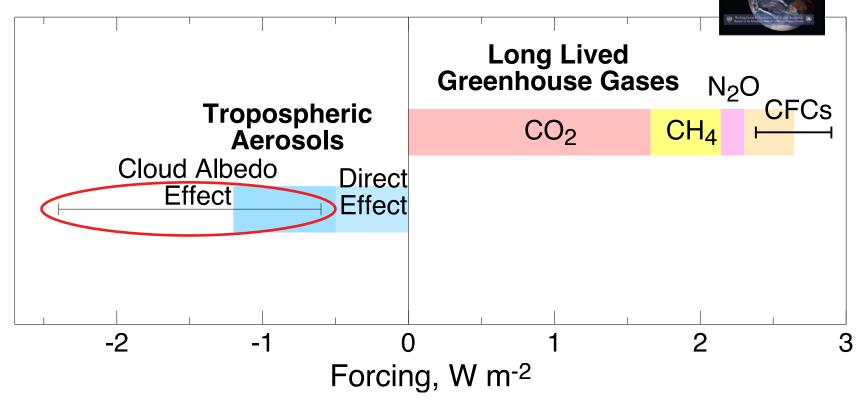
Extracted from IPCC AR4 (2007)



Aerosols exert a negative (cooling) forcing, opposite to greenhouse gases.

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

Extracted from IPCC AR4 (2007)

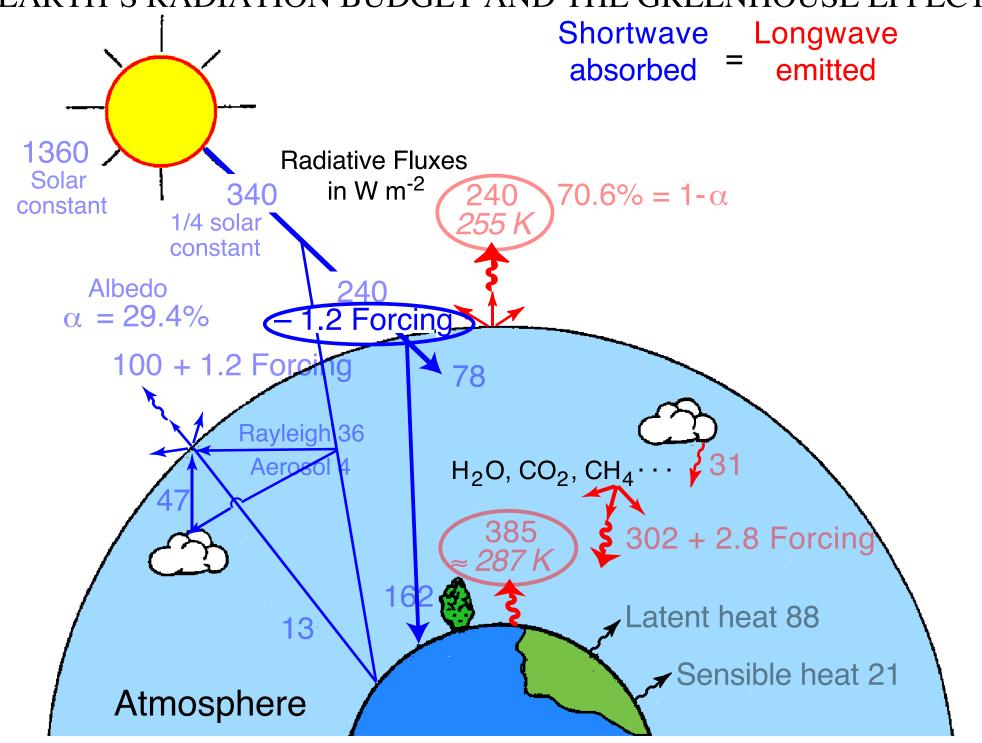


Aerosols exert a negative (cooling) forcing, opposite to greenhouse gases.

Aerosols are heterogeneous in space, time, composition, and size.

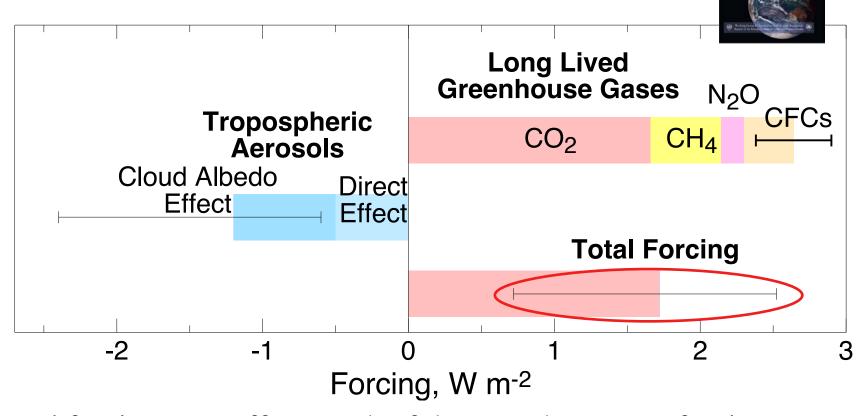
Uncertainty in aerosol forcing is much larger than uncertainty in greenhouse gas forcing.

EARTH'S RADIATION BUDGET AND THE GREENHOUSE EFFECT



CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

Extracted from IPCC AR4 (2007)

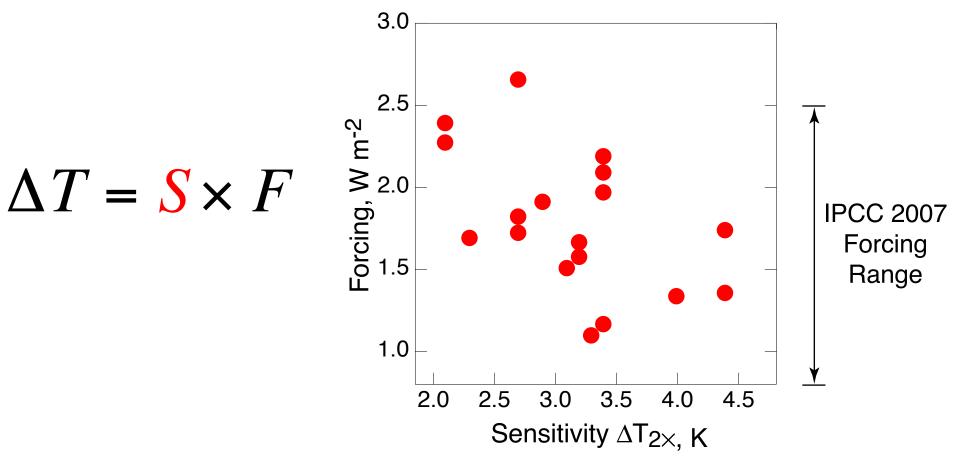


Aerosol forcing may offset much of the greenhouse gas forcing.

Uncertainty in total forcing is dominated by uncertainty in aerosol forcing.

CORRELATION OF FORCING AND SENSITIVITY IN CLIMATE MODELS

18 IPCC 2007 climate models



After Kiehl (2007); data from Forster and Taylor (2006)

To reproduce observed 20th century temperature increase, models with low sensitivity employed large forcing, and vice versa.

WHY HAS EARTH NOT WARMED AS MUCH AS EXPECTED...

FROM FORCING BY LONG-LIVED GREENHOUSE GASES?

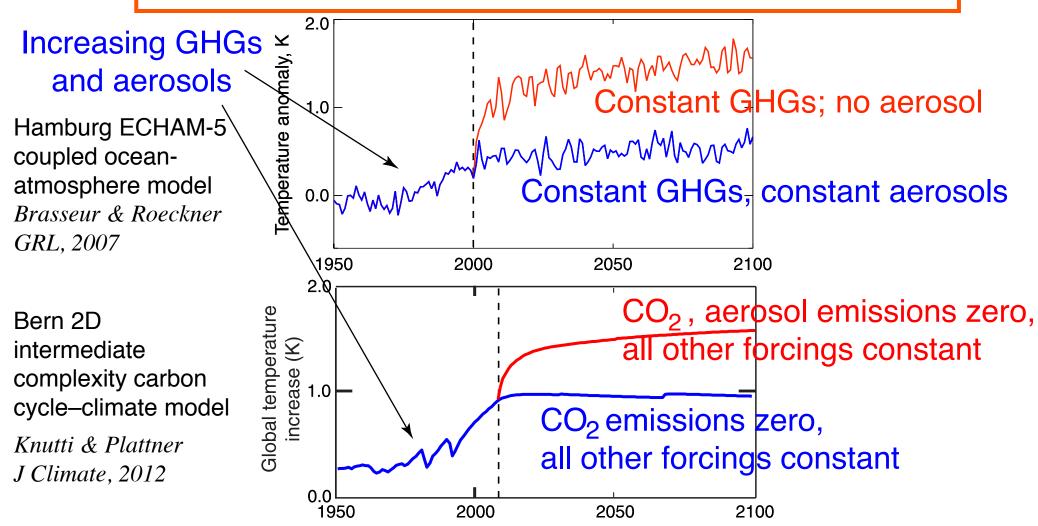
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- Countervailing natural cooling over the industrial period
- Lag in reaching thermal equilibrium. about 20 % of the discrepancy
- Countervailing cooling forcing by aerosols.
- Climate sensitivity lower than current estimates.

?? QUESTION ??

• Why is tguqnxkpi 'this so important?

USING CLIMATE MODELS TO ANSWER "WHAT IF" QUESTIONS

Turn off CO₂ emissions and aerosol forcing



Global temperature *rapidly increases* when aerosol forcing is halted.

?? QUESTION ??

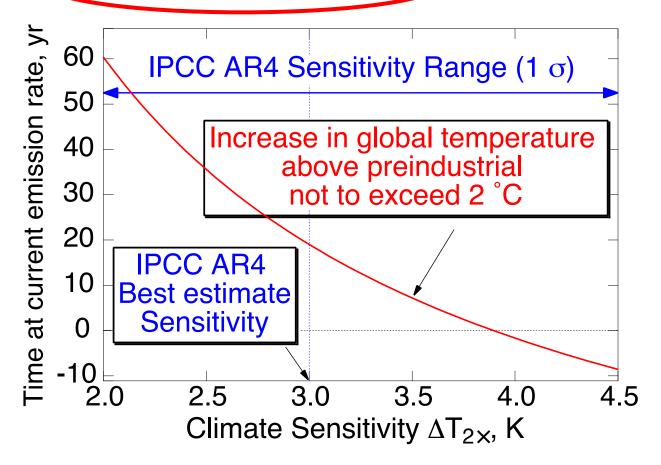
Why is all this so important?

KEY QUESTION

• How much more CO₂ can be emitted without committing Earth to a temperature increase of 2 °C above preindustrial?

ALLOWABLE FUTURE GLOBAL CO₂ EMISSION

Such that committed increase in global mean temperature not exceed 2°C Based on greenhouse gas forcing only, current forcing 2.8 W m⁻²



For IPCC best-estimate sensitivity, *only about 20 years* more emission at current rate.

For IPCC sensitivity range, allowable future emission at current rate ranges from +60 years to -10 years.

A Change in Temperature

Downward revisions in global warming estimates do not mean danger has been averted.

SINCE 1896, SCIENTISTS have been trying to answer a deceptively simple question: What will happen to the temperature of the earth if the amount of carbon dioxide in the atmosphere doubles?

Some recent scientific papers have made a splash by claiming that the answer might not be as bad as previously feared. This work — if it holds up — offers the tantalizing possibility that climate change might be slow and limited enough that human society could adapt to it without major trauma.

Several scientists say they see reasons to doubt that these lowball estimates will in fact stand up to critical scrutiny, and a wave of papers offering counterarguments is already in the works. "The story is not over," said Chris E. Forest, a climate expert at Pennsylvania State University.



NASA/GODDARD SPACE FLIGHT CENTER SCIENTIFIC VISUALIZATION STUDIO

Still, the recent body of evidence — and the political use that climate contrarians are making of it to claim that everything is fine — sheds some light on where we are in our scientific and public understanding of the risks of climate change.

Arctic Sea ice in 2008. Most climatologists predict a rise of five degrees Fahrenheit when carbon dioxide levels double. The topic under discussion is a number called "climate sensitivity." Finding this number is the holy grail of climate science, because the stakes are so high: The fate of the earth hangs in the balance.

The first to take a serious stab at it was a Swede named Svante Arrhenius, in the late 19th century. After laborious calculations, he declared that if humans doubled the carbon dioxide in the air by burning fossil fuels, the average temperature of the earth would rise by something like nine degrees Fahrenheit, a whopping figure.

He was on the high side, as it turned out. In 1979, after two decades of meticulous measurements had made it clear that the carbon dioxide level was indeed rising, scientists used computers and a much deeper understanding of the climate to calculate a likely range of warming. They found that the response to a doubling of carbon dioxide would not be much below three degrees Fahrenheit, nor was it likely to exceed eight degrees.

In the years since, scientists have been CONTINUED ON PAGE D6

ScienceTimes

The New York Times

ACKNOWLEDGMENTS









Many colleagues at BNL and elsewhere

www.ecd.bnl.gov/steve